Interactive e-Learning Tools and Pedagogy for Engaging STEM Education and Skills Development in the Digital Era: Challenges and Opportunities

Published in:
Proceedings of the 28th ICDE World Conference on Online Learning, WCOL-19

Publication Status:
Published (in print/issue): 01/01/2019

Document Version
Publisher's PDF, also known as Version of record

Interactive e-Learning Tools and Pedagogy for Engaging STEM Education and Skills Development in the Digital Era: Challenges and Opportunities

Yakov E. Cherner[1], James Uhomoibhi[2], Maija M. Kukla[3]

[1]ATeL – Advanced Tools for e-Learning, USA, [2]Ulster University, UK, [3]University of Maryland College Park, USA

Abstract

This paper presents and discusses e-learning tools and instructional approaches that are well adapted to habits of modern youth and the most advanced pedagogies. The tools promote exciting novel ways to engage students in interactive learning of STEM concepts in the context of their practical applications and acquire professional skills online.

The learning and training activities and virtual laboratories (v-Labs) immerse students in digital learning environments such as an Energy Efficient Smart House, Golf Course, Biomanufacturing Facilities, Automotive shop, and Leonardo Da Vinci's Distillation Laboratory. Students are involved in cross-disciplinary learning STEM subjects related to classical mechanics, solar energy, energy efficiency, Internet of Things (IoT), conventional and smart home appliances and systems, engines and turbines, bioprocessing and much more. Microeconomics and environment protection issues are considered as well.

The assignments are designed in a way that students acquire practical skills while gaining theoretical knowledge and developing deep understanding.

Students' and teachers' feedback - and our and our partners' observations - revealed that:

- Educational content capitalized on students' real-life experience helped learners comprehend STEM subjects and convince them that STEM knowledge and skills are within their grasp.
- Online experimentation prior to on-site hands-on practice enabled users to perform training and job tasks meaningfully, faster and with fewer mistakes.
- Project's hybrid laboratories were effective in engaging students and acquiring practical skills based on deep understanding.
- Reconfigurable self-guided online assignments made it possible to personalize learning activities and adapt them to student backgrounds and educational needs.
- Gamified learning activities were effective in engaging and motivating students and improved their overall learning experience, as well as in facilitating informal learning.

In summary, v-Labs are easy to use, and science becomes fun to learn. All interactive resources run on PCs and mobile devices and can be easily integrated into online courses including MOOCs.

Key Words: **Virtual laboratories, activity-based learning, STEM education, skills training, biopharmaceutical education and training, sustainable energy**

Introduction

The fast-changing digital technologies have a profound effect on our everyday life and transform workplace. These technologies bring unprecedented opportunities for delivering education and gaining knowledge and skills. In the modern digital society, STEM careers are often referred to as the jobs of the future, driving innovation, social wellbeing, inclusive growth and sustainable development. Nevertheless, in 2018 in the USA only 24% of teenaged boys and 11% of girls were willing to pursue a STEM career (Kim, 2018).

Outstanding challenges to quality STEM education include old-fashioned content and outdated teaching technology of its delivery are among them. Often STEM concepts are taught to students in a too academic (methodical yet dry and boring) format. This intimidates students and discourages them from pursuing a STEM career as science contexts appear rather complicated and irrelevant to real life and students' every-day experience (Kurfiss 1988, Learning (2017).

Our online learning and training systems and activity-based pedagogy have been designed to equip teachers with e-learning tools and advanced pedagogical strategy that match the learning preferences of students of digital generation and are capable to involve teens and young adults in gamified contextual STEM learning. All educational systems discussed in this paper facilitate contextual learning and are based on a constructivist theory of teaching and learning (Dimock & Boethel, 1999). They are designed in such a way that students are able to construct meaning based on their own experiences and convert information into knowledge through active observations, processing and interpretations (Cooper, 1993, Wilson, 1997).

With the current trend when students are moving from PCs to tablets and smartphones, all applications we discus here are cloud-based, they support both mouse and touch screen functionality, and can run on mobile devices under Windows, iOS or Android OS and do not require any plugins or expensive hardware.

This paper presents and discusses the examples of e-learning tools and approaches aimed to encourage digital natives - teens and young adults who increasingly rely on technology in their day to day life activities - to learn STEM concepts in the context of their practical applications and acquire professional skills online in an engaging interactive way.

Activity-based Contextual Learning

The activity-based immersive learning and training environment built around a "Virtual Energy Efficient Smart House" (v-EESHouse) (Fig. 1) has been designed to provide an interactive context for cross-disciplinary learning and teaching of many STEM topics related to solar energy, energy efficiency, Internet of Things (IoT), as well as to microeconomics and environment protection. The v-EESHouse consists of a series of interlinked virtual laboratories (v-Labs) that allow users to explore energy consumption by major home systems and appliances, get familiar with the IoT technology, and the use of solar energy for domestic needs. Thus, educational content and all learning activities are closely relevant to everyday experiences and engage students in studying STEM subjects in the context of their applications. The focus of V-labs on whole phenomena rather than on an isolated science topic helps students construct a deeper understanding of the world around them. Such a cross-disciplinary approach links the variety of fundamental scientific concepts and practical issues (e.g. Sun's seasonal path and its affect on the length of daytime in different regions, the dependence of electrical power generated by solar panels on the Earth's axial tilt and local variations in the atmosphere, the lows of thermodynamics and refrigerator operation, heat flow and convection and energy losses, etc.). Consequently, energy consumed by house systems and home appliances is linked to utility bills and hence naturally stimulates the energy-responsible behavior as well as brings up environmental issues.

Highly interactive and interconnected simulations form pillars of the v-EESHouse and all other cloud-based e-learning environments described in this paper. Each simulation incorporates a solid science/math model that accurately reproduces a design and operation of actual devices/systems, natural processes, or learning situations.

The v-EESHouse e-learning system enables instructors to create blended (or hybrid) laboratories that synergize learning effects of hands-on and online experimentation. In such labs, simulated parameters may be synchronized with measured physical data.

Beyond academic education, hybrid experiments involving cyber-physical systems (CPS) and IoT technology were employed for the professional training of technicians of utility industry and IoT service providers.

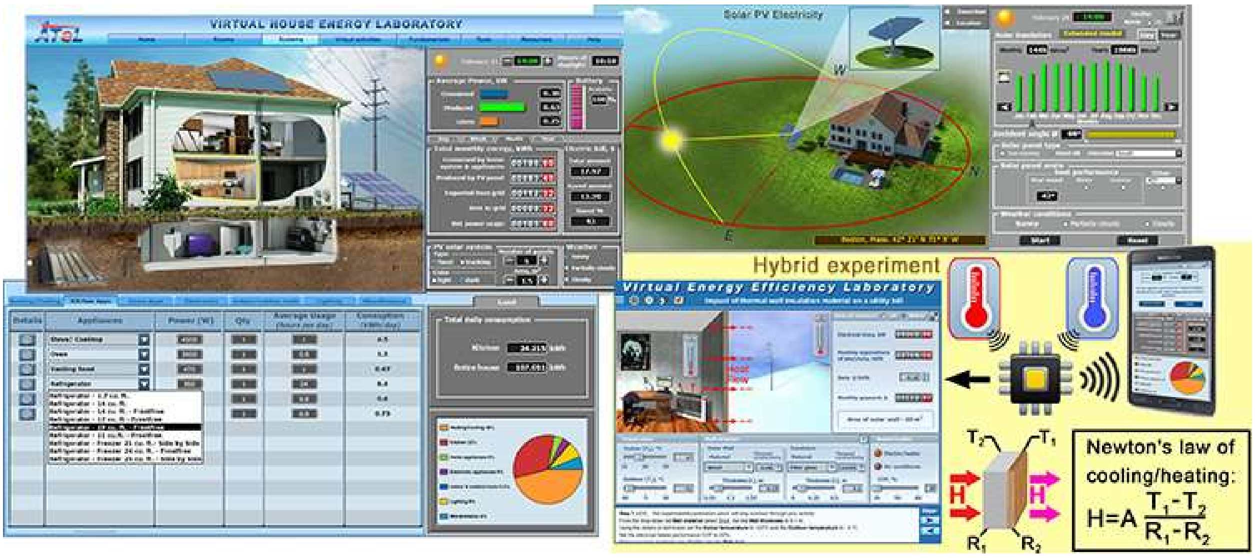

Figure 1. Screenshots of the v-EESHouse e-learning environment. The Dash Board (bottom right) dynamically displays amounts of energy consumed by the household, produced by solar panels, imported from and sent to grid, total electric bill amount and saved amount. Any system changes (e.g., a type, number and size of solar panel, weather condition, and electrical power load immediately affect the readings. The Load Calculator (bottom left) allows users to estimate how replacements of various home appliances, lightings, utility systems, etc. affect the energy consumption and a utility bill. The hybrid laboratory (bottom right) comprises the v-lab for investigating factors affecting a two-layer sandwich-type wall connected with physical thermosensors. Using a smartphone, students may control the virtual home appliances and residence HVAC systems and observe the results of these actions.

The v-EESHouse and other e-learning environments and individual v-Labs have been probed at different educational levels from middle and high schools to universities in the USA, UK, Tanzania, Ghana, Russia and some other countries. At the higher education level, these resources, in addition to science/engineering students, were tested by liberal art majors. The online activities proved to be useful for general public education and for professional training of employees of utility companies and IoT service providers. Depending on instructional patterns, settings, and audience, v-Labs and their components have been used for (i) homework and control assignments with traditional and blended courses, (ii) preparing students for hands-on work in real labs and workplaces, (iii) lecture demonstrations, and (iv) performance-based assessment of students' ability to apply gained theoretical knowledge and skills for solving practical problems.

Adaptable and personalized learning

One of the outstanding challenges in maximizing learning outcomes is to use a personalized e-Learning (U.S. National Plan, 2017). In contrast with a conventional "one size fits all" approach, our applications allow instructors to tailor and optimize learning objectives, content and assessments to be meaningful and appropriate for each individual learner. The employed concept of reconfigurable Self-contained OnLine Guided Assignments (SOLGAs), makes it possible to assemble student activities from cloud-based simulations and distributed component and adjust them to student ages, backgrounds and educational levels (from middle school to university).

Simulations are key components of a SOLGA, which is an integrated self-directed learning (or training) unit designed to achieve particular learning or training objectives. In addition to a main simulation, a SOLGA includes a step-by-step performance instruction, optional worksheet and task related documentation, links to databases, as well as an embedded assessment and associated multimedia learning resources for just-in-time learning. It may also include synchronized auxiliary simulations that extend the functionality of the main simulation (e.g. visualize hidden processes or explore phenomena from different perspectives). Simulations can exchange data and be synchronized with each other. The student is expected to follow a thorough set of step-by-step instructions to accomplish an educational assignment. The SOLGA framework may incorporate third-party simulations and other multimedia resources. The v-EENSHouse activities can facilitate the self-directed asynchronous learning, as well as synchronous instructor-led and/or collaborative learning. SOLGAs could also be easily integrated with various offline and online courses including those delivered via MOOC (massive open online course) platforms.

Gamified learning

Gamification is a proven way to involve youth and young adults in learning STEM and keep them engaged (Linch, 2017). We have implemented this approach in our e-learning module “Golf: Virtual Educational Playground”. It has been designed to help students study classical mechanics. Rather complex topics as vectors, trajectory, velocity, acceleration, momentum energy, resistance, etc. are studied in the context of golf game. Student assignments may require learners to make a prediction or solve a physics problem and instantly check the result by playing the game. In order to incentivize learners, rewards such as points, badging, leaderboards, etc. are used.

The module consists of two parts: ‘*Putt*’ and ‘*Chip shot*’ (Fig.2). The virtual lab ‘*Putt shoot*’ facilitates a wide range of activities focused on uniform and non-uniform motion along a straight line. Students observe and measure the impact of an initial ball velocity, inclination angle, and friction between the ball and the court ground surface on ball movement.

The ‘*Chip shot*’ v-Lab enables students to investigate projective motions. how angle and magnitude of the initial ball velocity, air resistance, wind speed and direction affect the ball trajectory, the elevation and the distance traveled. The learners can also explore forces acting on a ball. Graphics and diagrams bridge game-like activities with traditional subjects of physics and math and help students study and understand the concepts of vector, trajectory, velocity components, etc. Depending on scenario the level of assignment varies from very basic to advanced.

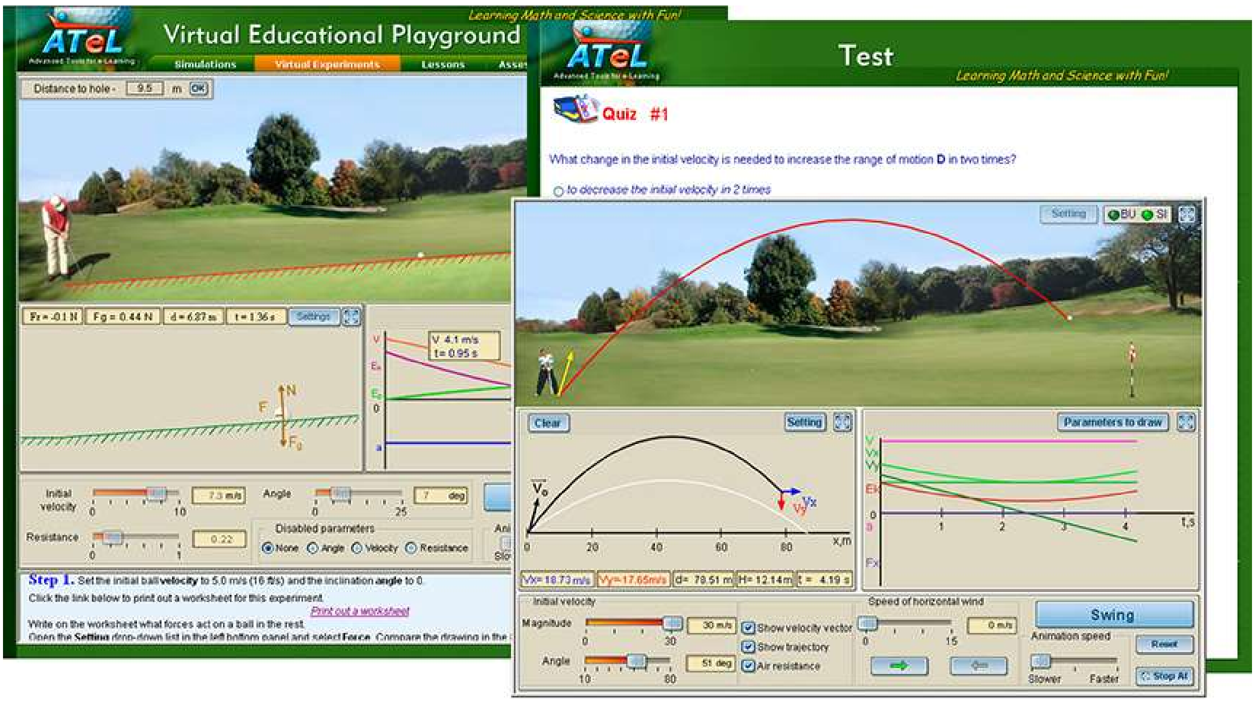

Figure 2. Screenshots of e-learning module “*Golf: Virtual Educational Playground*”. Both v-Labs ‘*Putt*’ (left) and ‘*Chip shot*’ (right) include a game panel (top) and two panels underneath for monitoring ball movement and dynamically presenting charts. Each panel can be zoomed-in to full screen.

Learning science in historical context

Unfortunately, science history is rarely taught in schools and even in higher education programs due to the lack of time (or motivation). In the meantime, exploration of scientific subjects in historical contexts, especially when a famous person is involved, often offers a “motivational hook”, which can encourage student to lean science. Undoubtedly, Leonardo Da Vinci is one of the most outstanding, mysterious and fascinating personalities of all times.

The educational module *Distillation in Historical Context* (Fig. 3) has been designed to spark an interest in science by considering some chemical and physics topics in historical contexts involving

Leonardo Da Vinci drawings and inventions. It is based on three original drawings of antic distillation devices called *alembics,* which bear the author's notes and are stored at the Biblioteca Ambrosiana di Milano (Da Vinci, 2003).

Students embark on their journey with a brief introduction to Da Vinci's bio, artworks and inventions. By exploring the design, operation and volatilities of the alembics along with Leonardo's notes students can understand how the genius worked on his inventions. Students can zoom in the picture to scrutinize drawings, and read Leonardo's backward mirror writings translated into English, compare an original drawing with the corresponding 3D models, zoom and rotate the models, and view their cross-section. AR (augmented reality) implementations of the drawings for handheld tablets or smartphones are available as well. Students have a chance to investigate how the distillation occurs in each device and analyze how Da Vici worked to improve his invention and consecutively overcame alembic shortcomings.

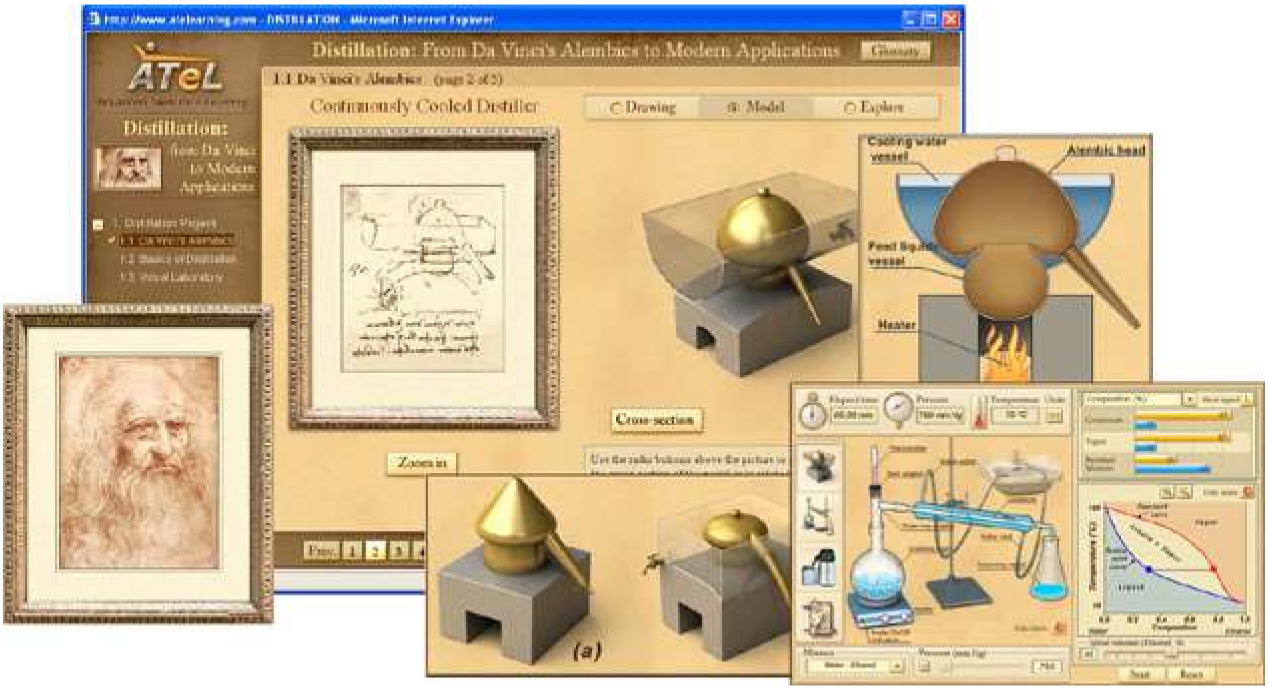

Figure 3. Screenshots of virtual labs on distillation that enable students to explore the distillation and its applications in historical context from Da Vinci's to modern time.

Students conduct authentic distillation experiments online using either Leonardo's alembics or modern chemical glassware. and thereby journey from medieval devices to contemporary laboratory equipment. Students collect virtual data and study such processes as evaporation, boiling and condensation in various liquids. They also investigate distillation processes in the binary systems of water and ethanol, toluene–benzene and some others.

Developing knowledge, practical skills, and deep understanding

I. Automotive technology

The integrated virtual environment "*Automotive Technology*" (Fig. 4) is another example of an e-learning system that allows students to develop theoretical knowledge and practical skills together. It has been designed to help students study the construction and functionality of the major systems and components of diesels, internal combustion engines, turbines, and power plants. The combination of a variety of tools and resources in one system serves to aid in mastering practical skills, acquiring technical knowledge and learning fundamental principles enables instructors to seamlessly link training and learning into a single educational process that fosters a student's deep understanding of basic principles and cause-and-effect relationships in engine design and operation.

Figure 4. The virtual experiment "Influence of Compression Ratio on Engine Operation Cycle" performed at the v-Lab "Internal Combustion Engine Design and Operation" (a). Gauges in the middle panel display the major engine parameters such as fuel consumption, torque, power, rotation speed, pressure, oil and water temperatures and oil pressure. The right panel dynamically presents thermodynamic diagrams of engine operation. The screenshot (b) shows a fragment of the virtual experiment that enables automotive engineers and technicians, as well as car drivers who are eager to know more about vehicle maintenance, to explore how piston ring wear impacts engine performance and efficiency. The v-Lab "Thermodynamic Cycles" allows the student to explore in detail the Carnot cycle (c), Otto cycle and Diesel cycles, as well as to compare them with each other (d).

The set of automotive technology v-labs enables students to investigate the connections between processes and events taking place inside an engine or turbine and the thermodynamic cycle it operates on, observe and analyze parameter changes at any stage of the cycle. This helps students better understand how these systems operate and what affects power and efficiency of different types of engines and turbines. By varying process parameters (e.g., temperatures, pressure, compression ratio, injected heat, etc.) and monitoring the visualized system response, the student can comprehend both the virtues and the shortcomings of various engines, system limitations, requirements to device maintenance, and much more.

II. Biomanufacturing

Virtual learning environments and v-Labs are especially useful in teaching students the fundamentals of processes with long timescales such as, for example, cell culture growth in biopharmaceutical manufacturing operations. Additionally, there is minimal feedback on the status of the culture during operation. Performing authentic experiments in a virtual environment with instant feedback and the opportunity for multiple repetitions allow students to develop an understanding of key relationships between critical parameters and help them better cement core concepts and process flow.

The cloud-based interactive and comprehensive e-learning environment "*Virtual Upstream Biomanufacturing*" (v-UBio) has been developed and implemented to address the needs of biopharmaceutical education and professional training. It includes a set of simulation-based v-Labs, virtual production line, as well as online lessons, assessments, a glossary, and supporting materials.

The v-UBio enables students to gain skills in performing typical workplace procedures, such as cell counting, inoculation, cell growth in bioreactors of different volumes, and much more. Students can also master the aseptic techniques of cell culture, and enhance their understanding of precautions and requirements to prevent cross contamination.

The use of the latest Web technologies made it possible to allow an instructor to monitor, in real time, how remote students to perform a virtual task online and instantly intervene when necessary. An embedded authoring tool enables the instructor to modify the experiment on the fly.

v-Labs can be linked and combined with handheld Augmented Reality objects (e.g., interactive AR bioreactor).

Figure 5. Screenshots of the e-learning modules that make up the "*Virtual Upstream Biomanufacturing*" environment. The v-Lab 'Inoculation' (a) helps students better understand the process and gain the practical skills necessary to perform the initial cell growth task. One of emphasizes is placed on aseptic techniques and culture transfer procedures (b). A series of 'Cell Growth' experiments (c) requires students to assemble the system, calculate and set up process parameter, as well as monitoring the process and keep it on track. The virtual exercise 'Cell Counting' (d) helps students develop skills for accurate and consistent cell counts. An animated assistant avatar (bottom right) provides immediate feedback, tips and comments.

The v-UBio environment also includes an interactive upstream process flowchart diagram that allows students to explore all upstream processing procedures in great detail, learn the requirements for executing the procedures, view relevant video clips, graphs, tables, and other relevant multimedia resources. This helps students build the ultimate "big picture" of upstream processing.

Work in Progress

We have recently initiated the research on what pedagogical principles are most efficient in providing different groups of students with the appropriate learning experience.

The v-EEHouse is being modified (in cooperation with university faculty from Ghana, Tanzania, and Nigeria) to fit local Sub-Saharan African realities and promote the use of renewable energy sources and clean cooking techniques. Interactive e-learning resources are also adjusted to specific requirements of African schools and universities. The goal is to help African students acquire knowledge and skills demanded at local job markets and contribute to sustainable socio-economic development through digital delivery strategies. Potentially, this approach may help transform the entire way of how education is gained and delivered in developing countries and globally. We also seek to promote efficient energy technologies and sources for African households and agriculture.

Conclusion

A comprehensive and consistent examination of the impact of the described tolls and pedagogy on students' learning of STEM subjects and their attitudes towards pursuing STEM careers were beyond the scope of our projects. Nevertheless, students' and teachers' feedback via questionnaires and surveys, as well as our partners' observations have brought us to the following conclusions:

- Educational content that capitalizes on students' everyday or/and workplace experience helps break traditional prejudices that some teens often have towards science and convince them that STEM knowledge and skills are within their grasp and useful in real life.
- Online experimentation prior to on-site hands-on practice had a proven positive effect on students' performance in actual labs and workplaces. The students felt more comfortable with equipment, knew how required procedures have to be executed. and fulfilled training and job tasks meaningfully, faster and with less mistakes.
- The skills, coupled with knowledge of processes and equipment operation, were more transferable and could be successfully applied to solve problems and carry out tasks different from the practiced tasks.
- Hybrid laboratories demonstrated a potential to enhance student engaging and connect the development of practical skills with a deeper understanding of underlying scientific and engineering concepts.
- Easy reconfigurable self-guided online assignments were very useful and efficient in individualizing the learning experience and adapting student activities to different cognitive styles and ways of learning that helped keep users engaged. In addition, the SOLGA concept made it possible to reuse complex simulations – most expensive components of quality interactive curricula.
- Gamified learning activities were effective at engaging and motivating students and improved their overall learning experience, making it fun and enjoyable.
- Gamified v-Labs and the labs based on a real-life context familiar to students provide extended (practically unlimited) learning opportunities and resources for informal education.
- According to feedback of faculty of the Department of Chemical and Biological Engineering at Tufts University, the virtual distillation lab combined with hands-on experiments on studying binary systems promoted deeper underrating of the distillation process and factors affecting its outcome.
- Testing the Solar Energy v-lab at the Massachusetts Institute of Technology (MIT) revealed that learning activities were more beneficial for deepening students' conceptual and technical understanding (e.g. factors affecting the efficiency of a solar power system) rather than helping them better memorize particular laws and perform scientific/engineering calculations (e.g. manually calculate solar insolation.)

In summary, V-labs are easy to use, and science becomes fun to learn.

Acknowledgements

We thank Prof. Bruce Van Dyke (Quincy College, MA) and Prof. Garry Mullett (Springfield Technical Community College, MA) for their contribution to the development of the virtual laboratories and testing them with their students. We are also immensely grateful to MIT Professors Robert Jaffe and Michael Cima who designed excellent online activities based on our v-Labs and integrated them into their MIT courses, one of which was released on the MOOC platform EdX. Their - and their students' - detailed feedback and recommendations were extremely useful to us.

We would also like to express our gratitude to Dr. Osei Darkwa (Teletech Institute of Technology, Ghana), and Prof. Leonard Fweja and Dr. Catherine Mkude (Open University of Tanzania and MOOCAfrica) for their collaboration and valuable discussions.

References:

Cooper, P. A., (1993), Paradigm shifts in designing instruction: From behaviorism to cognitivism to constructivism., Educational Technology, 33(5), 12-19

Dimock, K. V., Boethel, M., (1999) Constructing Knowledge with Technology, Southwest Educational Development Lab., Austin, TX. Retrieved on June 2019 from https://files.eric.ed.gov/fulltext/ED431398.pdf

Da Vinci Leonardo. (2003) Drawings Album, Veneranda Biblioteca Ambrosiana. Retrieved on June 2019 from: https://digilander.libero.it/debibliotheca/Arte/Leonardowork_file/page_02.htm

Kim, S. (2018) New Research Shows Declining Interest in STEM, Center for Digital Education, Retrieved on June 2019 from: https://www.govtech.com/education/k-12/New-Research-Shows-Declining-Interest-in-STEM.html

Kurfiss, J. G. (1988), Critical Thinking: Theory, Research, Practice, and Possibilities. ASHE-ERIC Higher Education Report No. 2, Washington, D.C. Retrieved on June 2019 from: https://files.eric.ed.gov/fulltext/ED304041.pdf

Learning from Student Voice: Are Students Engaged? (2017) Student Survey, YouthTruth. Retrieved on June 2019 from: https://youthtruthsurvey.org/student-engagement/

Lynch. M. (2017) How does Gamification effect the Learning Process? The Edvocate, Retrieved on June 2019 from: https://www.theedadvocate.org/how-does-gamification-effect-the-learning-process/

U.S. National Educational Technology Plan Update (2017), Future Ready Learning: Reimagining the Role of Technology in Education, , U.S. Dept. of Education, Retrieved on June 2019 from https://tech.ed.gov/files/2017/01/NETP17.pdf

Wilson, B. G., (1997), Reflections on constructivism and instructional design., In C. R. Dills & A. J. Romiszowski (Eds.), Instructional development paradigms (pp. 63-80). Educational Technology Publications, Englewood Cliffs, New Jersey